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CASEBOOK

OF

BIBHAS DE

THE GREAT

HYPOSTYLE HALL

OF

ELECTROMAGNETIC THEORY

Wisdom hath builded her house,
she hath hewn out her seven pillars:
Proverbs 9:1

Classical Electromagnetic Theory,
as made whole by me, can be seen as
a twelve-pillared worthy house.
My first paper in this series appeared in 1978.
Now is 2021. I have not seen a single citing of
these refereed papers by the physics
establishment – now gone off the deep end.

INTRODUCTION

First, think of Electromagnetic Theory as a set of effects in a set of mediums. Basically, we have three mediums:

Conductors
Dielectrics
Vacuum (absence of matter)

We are to discuss what effects occur in them and how.

The foundation of EM Theory was laid down more than a hundred and fifty years ago by the likes of Faraday, Ampere, Maxwell et al. This foundation has been added to twice since: Once by my teacher Hannes Alfvén, and again by me.

When you take one EM effect in one medium, you can view this as a pillar of EM Theory. When you arrange such pillars in a logical sequence, you have a hypostyle hall.

The effects we will speak of are the following:

Electromagnetic Waves
Electric Current ***J***
Electromechanical force in a magnetic field ***B***
Electromagnetic "Body" Waves in a magnetic field ***B***

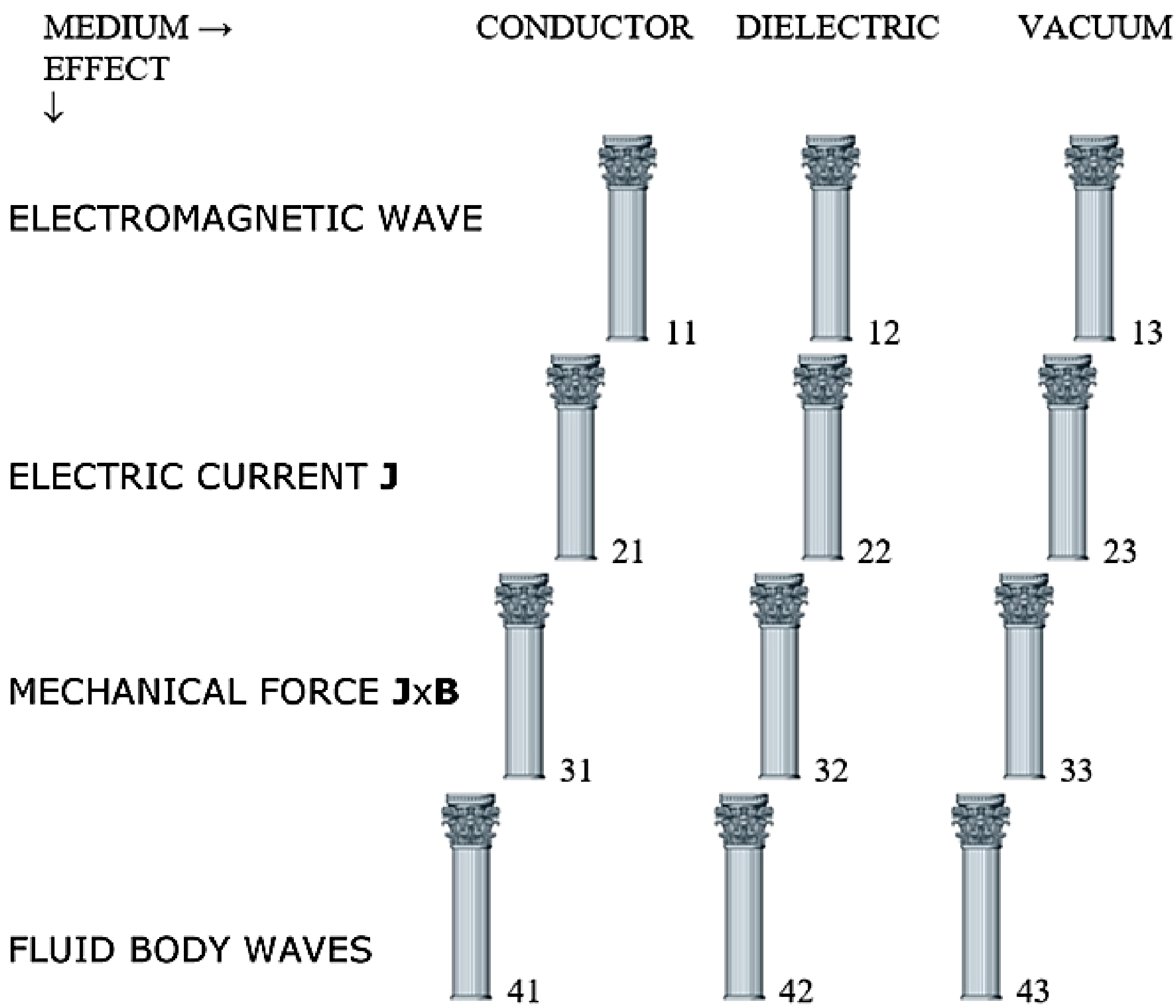
So, three mediums time four effects = 12 pillars!

The last of these effects refers to the case where the medium – if it is a fluid or a fluid analogue – moves as an EM disturbance propagates. In other words, this is a coupling of electromagnetic and "hydrodynamic" effects. I continue this idea to vacuum, deducing electromagnetic "companion waves."

04/30/2021

THE GREAT HYPOSTYLE HALL

THE GREAT HYPOSTYLE HALL OF ELECTROMAGNETIC THEORY



11 – EM Wave in conductors
12 – EM Wave in dielectric
13 – EM Wave in free space
21 – Conduction current J_c
22 – Polarization current J_p
23 – Displacement current J_o
31 – J_c x B force in conductore
32 – J_p x B force in dielectric (De, others)
33 – J_o x B force in free space (De)
41 – Magnetohydrodynamic (MHD) Wave (Alfven)
42 – Magnetohydroelectric (MHE) Wave (De)
43 – EM Companion Wave (De)

Bibhas De 04/30/2021

THE KEY PAPERS

Some of my key papers follow.

Magnetohydroelectric waves in a fluid dielectric

Bibhas R. De

Universities Space Research Association, Lunar and Planetary Institute, Houston, Texas 77058
(Received 30 May 1978; final manuscript received 1 September 1978)

A theoretical wave behavior in a magnetized fluid dielectric is deduced. The wave consists of oscillations of magnetic, kinetic, and electrostatic energies.

Consider a fluid dielectric substance placed in a uniform magnetic field, $\mathbf{B}_0$, in the positive z direction of a rectangular Cartesian coordinate system. The dielectric constant of the fluid is $\chi\epsilon_0$, where χ is the polarizability and ϵ_0 is the permittivity of free space. Now suppose that an electric field $\mathbf{E}$ increasing with time is applied in the positive x direction. This gives rise to a polarization current $\mathbf{J}_1=\chi\epsilon_0\dot{\mathbf{E}}$, and the consequent $\mathbf{J}_1\times\mathbf{B}_0$ force accelerates the fluid in the negative y direction to an instantaneous velocity $\mathbf{u}$. The charges in the polarized molecules of the dielectric are now subject to an additional equivalent electric field $\mathbf{E}'=\mathbf{u}\times\mathbf{B}_0$ (owing to the force $\mathbf{u}\times\mathbf{B}_0$ per unit charge), and a little consideration will show that the effect of this field is to drive a current $\mathbf{J}_2=\chi\epsilon_0\dot{\mathbf{E}}'$ in the direction opposite to $\mathbf{J}_1$. Thus, the net polarization current $\mathbf{J}$ measured in our coordinate system (in which $\mathbf{E}$ and $\mathbf{u}$ are measured) is

$$\mathbf{J}=\chi\epsilon_0[\dot{\mathbf{E}}+(\partial/\partial t)(\mathbf{u}\times\mathbf{B}_0)]. \tag{1}$$

Now consider an electromagnetic disturbance in the fluid. We write $\mathbf{u}=u_y\hat{y}$, $\mathbf{E}=E_x\hat{x}$, $\mathbf{J}=\mathbf{J}_x\hat{x}$, and $\mathbf{b}=b_y\hat{y}$, where $\mathbf{b}$ is the induced magnetic field. We assume $b\ll B_0$. Using Eq. (1), the two Maxwell's equations $\nabla\times\mathbf{E}=-\dot{\mathbf{b}}$ and $\nabla\times\mathbf{b}=\mu_0\mathbf{J}+\mu_0\epsilon_0\dot{\mathbf{E}}$, (where μ_0 is the magnetic permeability of free space) and Newton's law $\rho\dot{\mathbf{u}}=\mathbf{J}\times\mathbf{B}_0$ (ρ is the fluid mass density), we obtain the following relations

$$J_x=\chi\epsilon_0(\dot{E}_x+\dot{u}_yB_0), \tag{2}$$

$$\partial b_y/\partial z=-\mu_0J_x-\mu_0\epsilon_0\dot{E}_x, \tag{3}$$

$$\partial E_x/\partial z=-\partial b_y/\partial t, \tag{4}$$

$$\rho\dot{u}_y=-J_xB_0. \tag{5}$$

These equations may be solved simultaneously to give

$$\partial^2b_y/\partial t^2=V^2(\partial^2b_y/\partial z^2), \tag{6}$$

with

$$V^2=c^2\left(\frac{1}{\chi}+\frac{v_a^2}{c^2}\right)\left(1+\frac{1}{\chi}+\frac{v_a^2}{c^2}\right)^{-1}, \tag{7}$$

where c is the velocity of light, and $v_a=B_0/(\mu_0\rho)^{1/2}$ is a well-known parameter called the Alfvén velocity.[1] Equation (6) indicates a wave propagating with a velocity V, in which $\mathbf{b}$, $\mathbf{u}$, and $\mathbf{E}$ oscillate, corresponding to oscillations in magnetic, kinetic, and electrostatic energies. This wave may therefore be termed a magnetohydroelectric wave. The solutions for b_y, E_x, and u_y in the wave are

$$b_y=b_0\sin\omega(t-z/V), \tag{8}$$

$$E_x=b_0V\sin\omega(t-z/V), \tag{9}$$

$$u_y=-\frac{Vb_0}{B_0}\left(\frac{v_a^2}{V^2}-\frac{v_a^2}{c^2}\right)\sin\omega\left(t-\frac{z}{V}\right), \tag{10}$$

where b_0 is an arbitrary constant, and ω is the wave frequency.

The ratio ξ of the kinetic energy density $\rho u_y^2/2$ to the magnetic energy density $b_y^2/2\mu_0$ in the wave is

$$\xi=(v_a/V)^2(1-V^2/c^2)^2, \tag{11}$$

and the ratio η of the kinetic energy density to the electrostatic energy density $(1+\chi)\epsilon_0E_x^2/2$ is

$$\eta=(v_d^2v_a^2/V^4)(1-V^2/c^2)^2, \tag{12}$$

where $v_d=c/(1+\chi)^{1/2}$ is the velocity of electromagnetic waves in the dielectric in absence of the magnetic field $\mathbf{B}_0$. Thus, for $V\sim v_a\sim v_d\ll c$, the kinetic, magnetic, and electrostatic energies have comparable magnitudes. Some examples of fluids with large values of χ are H_2O ($\chi\approx80$), H_2O_2 ($\chi\approx84$), D_2O ($\chi\approx78$), and N_2H_4 ($\chi\approx52$).[2]

From Eq. (8) one can derive the velocity $u_{y,fl}$ of the magnetic fieldlines to be

$$u_{y,fl}=-(Vb_0/B_0)\sin\omega(t-z/V). \tag{13}$$

Note that this velocity equals u_y when $V^2\ll c^2$ (or $\chi\gg1$) and $V\approx v_a$. In this case a state of "frozen flow"[1] exists where the fluid and the magnetic field lines move together at the same velocity. Whether or not this state is practically realizable in a dielectric fluid is questionable.

The resemblance of the wave derived here to Alfvén waves (magnetohydrodynamic waves) in a magnetized conducting fluid is superficial. There is no logical limit in which the present wave reduces to an Alfvén wave, or vice versa. More generally, we may consider a partially conducting and partially dielectric fluid, and replace Eq. (2) by

$$J_x=\chi\epsilon_0(\dot{E}_x+\dot{u}_yB_0)+\sigma(E_x+u_yB_0), \tag{14}$$

where σ is the conductivity. Equations (14) and (3)–(5) may now be solved simultaneously to yield Eq. (6) with V replaced by V' where

$$V'^2=c^2\frac{\dfrac{1}{\chi}+\dfrac{v_a^2}{c^2}-i\dfrac{\mu_0\sigma}{\chi\omega}v_a^2}{1+\dfrac{1}{\chi}+\dfrac{v_a^2}{c^2}-i\dfrac{\mu_0\sigma}{\chi\omega}\left(1+\dfrac{v_a^2}{c^2}\right)c^2}, \tag{15}$$

where ω is the wave frequency. In the limit $\sigma\to0$, we have $V'=V$, and in the limit $\chi\to0$, $\mu_0\sigma c^2/\omega\to\infty$, we have $V'\to(v_a^{-2}+c^{-2})^{-1/2}$ which, when $v_a\ll c$, reduces to the Alfvén velocity.

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Vacuum electromagnetic interaction

B R De†‡

† Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, California 92093-0407, USA

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Abstract. The concept of a magnetic 'companion wave' arising when an electromagnetic wave is superimposed on a static magnetic field in vacuum is discussed. A conceptual device for observing vacuum electromagnetic momentum is proposed. The companion wave is then shown to be as real and observable as the electromagnetic wave, and also to have the possibility of carrying information.

1. Introduction

Electromagnetic (EM) interactions occurring in vacuum (e.g. an EM wave impinging on a static magnetic field) are at present thought to be an unobservable and hence inconsequential subtlety of the EM theory [1]. This view, however, is based on the non-existence of a device with which to observe vacuum electromagnetic interactions (hereinafter VEI). In this paper we show that VEI produces real and observable effects such as a heretofore unknown wave behaviour, and present the concept of a device with which to observe such waves. We begin with a discussion of certain developments in EM theory that lead us to take up anew the subject of VEI.

2. Background

The dielectric polarization current J_d, when extrapolated to vacuum, leads to the concept of vacuum displacement current, which is included in the fourth Maxwell equation, written here for a purely dielectric material in MKS units:

$$\nabla \times B = \mu_0 J_d + \mu_0 \epsilon_0 \dot{E} \tag{1}$$

where B and E are the magnetic and the electric fields, and μ_0 and ϵ_0 are the permeability and the permittivity of free space. This vacuum displacement current $J_0 = \epsilon_0 \dot{E}$ leads to electromagnetic waves in free space. A logical complement of this concept arises from a cumulation of evolving ideas to date. Out of a long-standing controversy regarding the form of electromagnetic energy-momentum tensor [2–5], and out of a series of experiments and related further controversy [6–15], at least one simple, clear fact seems now to emerge: a dielectric carrying a displacement current in a magnetic field is subject to a mechanical force $F_d = J_d \times B$ per unit volume. This provides the dielectric counterpart of the $J \times B$ force in a conductor ($J =$ the conduction current). This force has been used, for example,

‡ Address for correspondence. PO Box 1636, Laguna Beach, California 92652, USA.

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to develop the dielectric counterpart of magnetohydrodynamics [16–19]. It is instructive to examine the consequence of extrapolating this dielectric force to vacuum.

By taking the cross product of both sides of equation (1) with $\boldsymbol{B}$, we have

$$(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \mu_0 \boldsymbol{F}_{\mathrm{d}} + \mu_0 \epsilon_0 \dot{\boldsymbol{E}} \times \boldsymbol{B}. \tag{2}$$

This is the 'force equation' corresponding to equation (1) or the 'current equation'. The right-hand side includes a term $\boldsymbol{F}_0 = \boldsymbol{J}_0 \times \boldsymbol{B}$ that has the dimensions of a force, and needs interpretation. We now proceed to show that just as the last term of equation (1) leads to real and observable EM waves in vacuum, the last term of equation (2) leads to real and observable magnetic pressure or energy density waves that accompany the EM waves.

3. An electromagnetic companion wave

We consider a plane EM wave propagating in free space in a region of a homogeneous static magnetic field $\boldsymbol{B}_0$ parallel to the z direction of a Cartesian coordinate system. The electric and the magnetic field amplitudes of the wave propagating in a direction r may be written as

$$\boldsymbol{E} = \boldsymbol{E}_0 \sin(\omega t - k_0 r) \tag{3}$$

$$\boldsymbol{b} = \boldsymbol{b}_0 \sin(\omega t - k_0 r) \tag{4}$$

where E_0 and b_0 ($= E_0/c$, c =the velocity of light) are the amplitudes, ω is the circular frequency and $k_0 = 2\pi/\lambda_0$ is the propagation constant (λ_0 =the wavelength). The instantaneous net magnetic field is $\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{b}$. The instantaneous energy flow in the medium is given formally by the Poynting vector

$$\boldsymbol{S} = (\boldsymbol{E} \times \boldsymbol{B})/\mu_0. \tag{5}$$

Unless otherwise specified, we assume in the following discussion a region of space that is so far removed from the sources of the static magnetic field and the EM wave that the time-scale of interaction between the wave and the magnetic field is much shorter than the time needed for these sources to sense this disturbance. Stated differently, we assume that the sources do not contribute to local energy conservation during the interaction.

We next consider successively the following three situations: the wave propagates in the z direction, and the magnetic field $\boldsymbol{b}$ is parallel to the x axis; the wave propagates in the y direction, and the magnetic field $\boldsymbol{b}$ is parallel to the x axis; the wave propagates in the x direction and the magnetic field $\boldsymbol{b}$ is parallel to the z axis. Then the instantaneous Poynting vectors for the above three cases are, respectively,

$$\boldsymbol{S}_z = (c/\mu_0) b_0^2 \sin^2(\omega t - k_0 z) \hat{\boldsymbol{a}}_z \tag{6}$$

$$\boldsymbol{S}_y = (c/\mu_0) b_0^2 \sin^2(\omega t - k_0 y) \hat{\boldsymbol{a}}_y \tag{7}$$

$$\boldsymbol{S}_x = (c/\mu_0) b_0^2 \sin^2(\omega t - k_0 x) \hat{\boldsymbol{a}}_x + (c/\mu_0) B_0 b_0 \sin(\omega t - k_0 x) \hat{\boldsymbol{a}}_x. \tag{8}$$

Thus the wave travelling in the x direction involves a component of energy that travels back and forth. It is an interaction energy in that it involves the wave magnetic field $\boldsymbol{b}$ and

the ambient magnetic field $\boldsymbol{B}_0$, and can, in principle, be arbitrarily large compared with the energy flow of the wave itself, i.e. the first term in equation (8).

The Poynting vector sometimes represents a real energy flow (as in the case of EM waves) and sometimes it is only a mathematical term (as when both the electric and the magnetic fields are static). To ascertain which is the case in the present instance, we note that the above result can also be arrived at from first principles without reference to the Poynting vector, from simple work–energy considerations. The total energy density $u_\perp$ upon establishing a magnetic field b perpendicular to a pre-existing field B_0 is simply the sum of the energy densities of the two fields:

$$u_\perp = (B_0^2 + b^2)/2\mu_0. \tag{9}$$

However, the net energy density when the two fields are parallel or antiparallel is

$$u_\parallel = (B_0^2 + b^2 \pm 2B_0 b)/2\mu_0. \tag{10}$$

The last term in parenthesis represents the work performed by the wave on the ambient field or vice versa. This is the interaction energy density U:

$$U = B_0 b/\mu_0. \tag{11}$$

This term, when multiplied by c, is the same as the last term in equation (8). It represents a spatial and temporal oscillation of the magnetic pressure or magnetic energy density in the medium, the energy being transported back and forth with velocity c, and parallel to the direction of wave propagation. This can also be seen by considering a box enclosing a volume V, with its sides parallel to the coordinate planes making up the surface A. From equations (8) and (10), and leaving out the energy balance for the electromagnetic wave, we can derive the following energy conservation relation:

$$\int \dot{U}\,\mathrm{d}V = \int \boldsymbol{S}_{\mathrm{xc}} \cdot \hat{n}\,\mathrm{d}A \tag{12}$$

where $\boldsymbol{S}_{xc}$ is the last term of equation (8), and $\hat{n}$ is the surface normal. The energy transport has certain characteristics of an EM wave in that it represents energy propagating at a velocity c, has a periodicity in time, and involves orthogonal electric and magnetic fields. It is not a modified form or a variant of conventional EM waves, but is something that exists in addition to, and in association with, such waves. In this sense it is a 'companion wave'. While the concept of an EM wave follows from the last term in the current equation (1), that of the companion wave follows from the last term in the force equation (2). Since no energy is being created or absorbed in the medium, the time average of U over one period or its space average over one wavelength must be zero. The companion wave is associated with compressions and rarefactions of the magnetic line of force, much like magnetosonic waves [20].

By applying equation (2) to the case that B_0 is parallel to b, and using the Maxwell's equation $\nabla \times \boldsymbol{E} = -\dot{b}$, we obtain

$$\ddot{U} = c^2 \frac{\partial^2 U}{\partial x^2} \tag{13}$$

which is the wave equation for the companion wave. Or, simply dividing both sides of the above equation by B_0, we obtain the wave equation for the b field of the EM wave. This shows the nature of the interdependence of the two waves.

4. Observability of vacuum electromagnetic interaction: the force-measuring antenna

Today, EM waves—in particular radio waves—would also be considered inconsequential had it not been for a device with which to observe these waves: an antenna. In the same way, the companion wave becomes consequential when we conceive of a corresponding device: a force-measuring antenna (FMA).

An FMA detects both EM waves and EM momentum. Its concept is simple: it is an antenna mounted in a force-measuring device which is mounted on a rigid body fixed in space (figure 1). Consider for simplicity an FMA made of an ideal short electrical dipole [22] of length L ($\ll \lambda_0$), placed parallel to the electric field vector of the EM wave. The current $\boldsymbol{I}$ induced by this wave is uniform along the dipole and is proportional to the electric field $\boldsymbol{E}$. Then the $\boldsymbol{I} \times \boldsymbol{B}$ force on the antenna is found to be

$$f = ALcb^2\hat{a}_x + ALc\mu_0 U\hat{a}_x \qquad (14)$$

which is directed parallel to the direction of wave propagation. Here A is a constant related to the antenna.

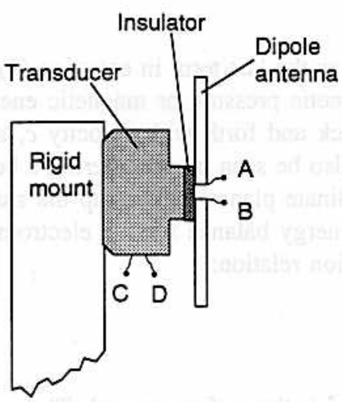

Figure 1. The conceptual force-measuring antenna. The transducer produces a voltage at the terminals CD, proportional to the force on the antenna and having the same sign. The companion wave appears at these terminals. The conventional EM wave appears at the terminals AB of the antenna.

It is now necessary to analyse the origins of such a force on an antenna placed in a magnetic field, i.e. to ask what the agent exerting this force is. If the antenna is in transmission, the agent is the generator. The force experienced by an antenna *on reception* can only arise from a momentum existing in free space. The first term on the right-hand side of equation (14) is clearly a unidirectional force associated with the momentum of the EM wave, and the observation of this force would verify the existence of this wave. The second term is associated with the companion wave. Both these forces will appear as voltages at the terminals CD of the FMA. The second term is distinguishable from the first by the bidirectional nature of the latter. We thus find that the momentum of the companion wave is as real and observable as that of the EM wave, and is not a mathematical artifact.

The above discussion leads us to a related observational consequence. On the face of it, equation (14) is valid whether the magnetic field B_0 is a distended field over many wavelengths as we have pictured, or just a local field at the antenna covering a region

much smaller than a wavelength. According to the present discussion, we do not expect the companion wave to fully develop in the latter case, and hence the force detected by an electrically small antenna (i.e. an antenna having a physical size much smaller than the wavelength) should be different in the two cases. From conventional electromagnetic theory, however, it is not immediately clear why this should be the case. We are thus left with a puzzling but testable prediction with regard to the companion wave. This test could be an experimental one, or it could be a theoretical proof that the $\boldsymbol{I} \times \boldsymbol{B}$ force on an electrically small antenna on reception is dependent on the extent of the magnetic field. The crux of such a proof may be the fact that even for an electrically small antenna, the effective collecting aperture (i.e. the area over which the antenna intercepts the incoming radiation) still has a dimension comparable to a wavelength [21].

5. Companion wave communication

We consider two points along the x axis: a source point S and an observation point O. An FMA is located at the point O. If the EM wave is modulated with the signal at S, then this signal will appear in both terminals AB and terminals CD of the FMA. Now we wish to study the possibility of similar information transfer through the companion wave.

At the source point S, let us modulate the static magnetic field $\boldsymbol{B}_0$ with a superimposed 'signal' $\Delta \boldsymbol{B} = \Delta \boldsymbol{B}_0(\boldsymbol{x}) \sin \nu t$, where the function $\Delta \boldsymbol{B}_0(\boldsymbol{x})$ is non-zero only in the source region and is zero at the observation point O. There will be an electric field associated with the time-varying magnetic field, but we assume that the variation is slow enough that no electromagnetic radiation is emitted. For the present theoretical discussion, it is not necessary to specify a source mechanism except to note that this mechanism is continually injecting energy into the source volume. Now, replacing $\boldsymbol{B}_0$ by $\boldsymbol{B}_0 + \Delta \boldsymbol{B}$ in equation (8), we find an additional flow term corresponding to $\Delta \boldsymbol{B}$:

$$S_{xs} = (c/\mu_0)\Delta B_0(x) b_0 \sin \nu t \sin(\omega t - k_0 x)\hat{a}_x. \tag{15}$$

Clearly, this can represent a unidirectional flow of energy out of the source region. This means that the signal ΔB propagates out of the source region. The mechanism is a spreading of magnetostatic oscillations, and represents a mode of energy propagation that is different from EM waves. This signal will appear only at the terminals CD of the FMA at O as a modulation of the momentum of the 'carrier' companion wave.

6. Applicability considerations

The foregoing discussion may now be made somewhat concrete. We note now that piezoelectric and acoustoelectric transducers today can measure ultrasonic vibrations at frequencies ranging to about 10 MHz while capacitive transducers range to well above 100 MHz [22]. For a numerical estimation of the magnitude of the force on an antenna due to the companion wave, suppose that our test dipole is lossless and is connected to a matched load. Its radiation resistance is $R = 80\pi^2(L/\lambda_0)^2$, so that the current is $I = V/2R \approx EL/2R$, where V is the voltage induced on the antenna [21]. The force due to the companion wave is $f_c = ILB_0$. From these relations, we find

$$f_c \approx 6 \times 10^{-4} E B_0 \lambda_0^2.$$

As an example, for an antenna in the earth's magnetic field ($B_0 \sim 0.5 \times 10^{-4}$ T), and subjected to an EM wave of flux density 1 W m^{-2} ($E_0 \approx 30$ V m^{-1}) at 1 MHz, the peak value of f_c is about 0.1 N. If the mass of the antenna is 1 kg, this is equivalent to an acceleration of $0.01g$ (g = the acceleration due to gravity), which should be detectable. One may then speculate on whether or not companion wave communication in the earth's magnetic field is a feasible technique.

7. Remarks

We return finally to equation (2). Our discussion makes it clear now that if equation (1) contains the essence of EM waves, equation (2) contains the essence of VEI. Thus, even though a derivative of equation (1), equation (2) has its own special import. The clue to that import is contained in the dielectric force we discussed at the outset.

Acknowledgments

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RAPID COMMUNICATION

A new mode of radio communication

B R De

Telesis Scientific, P O Box 1636, Laguna Beach, CA 92652, USA and
Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093, USA

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Abstract. Aspects of electromagnetic theory proposed recently point to a possible new mode of radio communication. Such communication would occur via a 'companion wave', a heretofore unknown wave behaviour associated with a radio wave propagating in a superimposed magnetic field. A method of realizing this mode of communication within conventional radio science is outlined.

It has been proposed recently that pulsed magnetic energy may spread limitlessly in free space through the agency of a conventional electromagnetic (EM) wave and a newly derived companion wave [1]. The latter is a real and observable energy density wave generated when an EM wave propagates with its magnetic field parallel to an external magnetic field. This companion wave can carry radio signals in addition to and distinct from those carried by the EM wave, even after the EM wave signal-carrying capacity has been fully utilized. Conceivable realms of applicability of this idea include wireless communication of all types.

The present communication reports two further results, both of which have the effect of bringing the original idea closer to the realm of applicability. The first concerns the original assumption of the presence of a pervasive static magnetic field (such as the Earth's magnetic field) between the points of transmission and reception. This assumption was made for the purpose of intuitive development of the idea. That restrictive requirement is now removed. Second, the concept of a new device called the *force-measuring* antenna was introduced to demonstrate the observability of the companion wave. The companion wave signal is now shown to be observable within conventional radio science using conventional antennae, without necessitating the new device.

To give the discussion specificity, figure 1 shows a transmitting electric dipole antenna T and a similar receiving antenna R separated by a distance D in a rectangular coordinate system. The transmitted electric and magnetic fields at any location $\boldsymbol{r}$ are

$$\boldsymbol{e} = \boldsymbol{e}_0(\boldsymbol{r})\sin(\omega t - kr) \quad (1)$$

$$\boldsymbol{b} = \boldsymbol{b}_0(\boldsymbol{r})\sin(\omega t - kr) \quad (2)$$

where $\omega = 2\pi f$ (f is the frequency of the wave), $k = 2\pi/\lambda$ (λ is the wavelength), and e_0 and b_0 are the field amplitudes. In the presence of an external magnetic field $\boldsymbol{B}(\boldsymbol{r})$, there arises a theoretical interaction energy density term (considered so far to be an unobservable mathematical subtlety of the EM theory):

$$u(\boldsymbol{r}) = \boldsymbol{B}(\boldsymbol{r}) \cdot \boldsymbol{b}(\boldsymbol{r})/\mu_0 \quad (3)$$

μ_0 being the magnetic permeability of free space. The flux of EM wave energy at any point on the x axis is given by the Poynting vector

$$\boldsymbol{S}(x) = \boldsymbol{e}(x) \times \boldsymbol{b}(x)/\mu_0$$

or

$$\boldsymbol{S}(x) = (c/\mu_0)b_0^2(x)\sin^2(\omega t - kx)\,\boldsymbol{a}_x \quad (4)$$

where c is the speed of light. It has been shown on straightforward theoretical grounds that there is an *additional* energy flux $\boldsymbol{s}(x) = cu(x)\boldsymbol{a}_x$ that is just as real and as observable as $\boldsymbol{S}(x)$. On assuming for a moment that $\boldsymbol{B}$ is uniform and parallel to $\boldsymbol{b}$, one obtains

$$\boldsymbol{s}(x) = (c/\mu_0)Bb_0\sin(\omega t - kx)\,\boldsymbol{a}_x. \quad (5)$$

This is an energy density wave that accompanies the EM wave (and hence the name companion wave), representing a sloshing back and forth of the interaction energy u at the speed of light. There is no net unidirectional propagation of this energy. The electric and magnetic fields of the EM wave remain unaffected, and no additional fields arise. In order to achieve communication in the companion wave mode, however, there must be unidirectional propagation and there must arise new field components. This can be achieved by having the field $\boldsymbol{B}(\boldsymbol{r})$ generated in a localized source region, and by making this field time-varying. The result is a pumping of energy into the companion wave mode.

The conventional radio signal Q may be considered here as being sent through the flux $\boldsymbol{S}$ by making the

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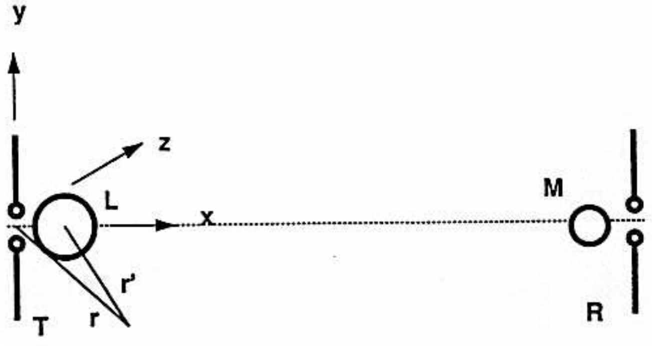

Figure 1. Conceptual arrangement for transmitting and receiving signals in both radio wave and companion wave modes. T and R are transmitting and receiving electric dipole antennas, L is a non-radiating current loop producing an oscillating magnetic field, and M is a magnetic antenna that senses time-varying magnetic fields (not drawn to scale).

amplitude $b_0(x)$ a function of time at the origin, $b_0(0, t)$. The question now arises of whether or not a *different* signal Q' may be sent simultaneously through the flux s by making B a function of time at the point of transmission, $B(0, t)$. To examine this, let a sinusoidally time-varying magnetic field be produced near the origin (at T) in a source volume by a non-radiating current loop L with its axis parallel to the z axis and its centre at $x = a$ in front of the dipole. The term non-radiating means that, at the frequency of operation of the loop and under normal circumstances, the entire EM energy fed to the loop by a generator oscillates between the loop and the generator, with a negligible portion of the energy escaping as the EM wave. The source volume is that approximate volume outside which the magnetic field due to the loop is undetectable. Let l be the linear extent of the source volume (l is about equal to the diameter of the loop), and let $l < \lambda/2$ (see discussion later) and $l \ll D$. Thus, at R there is no measurable magnetic field due to the loop. Since the electric field due to the loop is $E \simeq \nu l B$ (ν is the angular frequency of excitation of the loop), the ratio of the electric and magnetic energy densities is $E_e/E_m \simeq \nu^2/l^2c^2$. Thus, if l is kept much smaller than the wavelength at frequency ν, then the electric field E is unimportant for the present discussion and the energy of the loop is predominantly magnetic energy. The loop magnetic field $\boldsymbol{B}$ is now written as

$$\boldsymbol{B}(\boldsymbol{r}') = \boldsymbol{B}_0(\boldsymbol{r}')\sin(\nu t + \phi) \tag{6}$$

where B_0 is the amplitude, ϕ is a phase angle and $\boldsymbol{r}'$ is referred to the origin shifted to $x = a$. The functional forms of $\boldsymbol{b}_0(\boldsymbol{r})$ and $\boldsymbol{B}_0(\boldsymbol{r}')$ are well known [2]. The resultant interaction energy density is

$$u(\boldsymbol{r}) = \boldsymbol{B}_0(\boldsymbol{r}') \cdot \boldsymbol{b}_0(\boldsymbol{r})\sin(\omega t - kr)\sin(\nu t + \phi)/\mu_0. \tag{7}$$

Any direct coupling between the antenna and the loop (namely mutual coupling) or scattering of the EM wave by the loop is not included in the present discussion. A simple examination of the magnetic field line geometries shows (as can be verified by numerical integration) that the time-averaged power out of the source volume

$$P = \left\langle \int u(\boldsymbol{r})\,\mathrm{d}V \right\rangle_T \Big/ T \tag{8}$$

where $T = 2\pi/\nu$, can be made a non-zero positive quantity. Since it has already been established that this energy flow is real and observable, it follows that the energy will propagate *unidirectionally* out to infinity. As this energy travels at the speed of light, the signal Q' (in the form of a modulation of B_0) will arrive at R after a time $t_0 = D/c$, at the same time as the signal Q arrives. Any contribution to P from an $\boldsymbol{E} \times \boldsymbol{b}$ Poynting term is negligible if $B \simeq b$ and $E \ll e$ (see later discussion). There are no known effects that would guarantee that P remain identically zero under all circumstances.

Since the two primary sources of energy in the medium are the EM wave energy and the magnetic energy of the loop and since the EM wavefields remain unaffected by the interaction, it follows that a unidirectional spatial spreading of the interaction energy can occur only if a portion of the magnetic energy in the field of the loop expands in space with time (at the expense of the generator that powers the loop). At R there arises a *propagated* magnetic field (with its associated electric field) from the loop that would not arise in the absence of the EM wave. This is the physical process by which the signal Q' is conveyed. In terms of magnetic field line imagery, one may imagine the field lines due to the loop ballooning out in space in a pulsating fashion.

Since Maxwell's equations are linear, they allow spatial expansion of the energy in the manner described above. The propagated fields $\boldsymbol{B}$ and $\boldsymbol{E}$ at a distance point are what would normally exist if the current in the loop were much stronger. The emergence of these new fields at distant points in space is required by energy conservation. If the presence of these fields is accordingly allowed for, then the principle of superposition of EM fields is not violated: the field at any distant point is the sum of the EM wavefield and the companion wave signal field. For the latter mode of energy propagation, $E \ll cB$ whereas, for the EM wave, $e = cb$. Thus the concept of a wave impedance should not be applied to propagation of the companion wave *signal*.

In the original discussion [1], a static magnetic field existing in the entire region between T and R was assumed to generate a 'carrier' companion wave (see equation (5)) to be modulated by the signal B. It is now seen that the static magnetic field is unnecessary, and that the EM wave serves as the carrier for both the EM wave signal and the companion wave signal.

The practical problem of generating a companion wave is a problem of achieving a compromise between maximizing the power P while keeping ν substantially below ω. The latter condition ensures that l is much smaller than the wavelength at the frequency ν, while still $l \leqslant \lambda/2$. The placement of the loop in relation to the

electric dipole is an important factor in determining P, and should be outside the near zone (the non-propagation zone) of the dipole. The condition $l \leqslant \lambda/2$ arises from the fact that the field B has to perform work on, or oppose, the field b when the latter is increasing in strength with time over a half-wavelength segments in space.

At the receiving location $x = D$ there arise the EM wavefields

$$b(D,t) = b_0(D,t)\sin(\omega t - kD)\,a_z \tag{9}$$

$$e(D,t) = e_0(D,t)\sin(\omega t - kD)\,a_y \tag{10}$$

and the companion wave signal fields

$$B(D,t) = B_0(D,t)\sin(\nu t + \phi')\,a_z \tag{11}$$

$$E(D,t) = E_0(D,t)\sin(\nu t + \phi')\,a_y \tag{12}$$

where ϕ' is a phase angle, and the signals are contained in the amplitudes (Q in b_0 or e_0, Q' in B_0 or E_0). It should be noted that, while the x-dependence of B and E (included above in its entirety in the amplitudes B_0 and E_0) has a periodicity, this dependence is not necessarily sinusoidal. This dependence is determined by the source mechanism (the integration in equation (8)). The angle ϕ' is also determined by this integration.

The companion wave signal B or E can now be received by conventional antennae, without necessitating a force-measuring antenna. The receiving dipole R will sense the electric fields while a magnetic antenna (shown here as a loop M) will sense the magnetic fields. It will be seen below that $B_0 < b_0$, so that $E_0 \ll e_0$. Thus, the dipole may not experience the signal Q' at all. The loop M will register a superposition of Q and Q'. Knowing Q from the dipole, the two signals can be separated. More conveniently, the disparity between ω and ν may be exploited to receive only Q with dipole, and only Q' with the loop, by tuning or filtering. This disparity may also help any unwanted mutual coupling between T and L.

It has been suggested that the companion wave is observable with present-day technology [1]. The criteria for feasibility of companion wave communication over a given distance D may be developed along the following lines. From simple energy conservation arguments it follows that an estimate for $B_0(D)$ is

$$B_0(D) \simeq B_0(0)F^{1/2}G^{1/2}l/D$$

where G is the gain of the electric dipole and

$$F = P(\nu < \omega)/P(\nu = \omega)$$

is a theoretical efficiency factor (< 1) that can be evaluated numerically. It is now to be noted that the signal field $B_0(0)$ should not exceed the carrier field $b_0(0)$. Assuming that $B_0(0) \simeq b_0(0)$ leads to

$$B_0(D) \sim b_0(D)F^{1/2}$$

which allows one to estimate the strength of the companion wave signal in terms of the known strength of the conventional radio signal. For an order-of-magnitude estimate, one can make simplifying assumptions in equation (8) to obtain

$$\mathrm{O}(F) \simeq \int_0^T \sin(\omega t)\sin(\nu t)\,\mathrm{d}t \Big/ \int_0^T \sin^2(\omega t)\,\mathrm{d}t$$

which is readily evaluated.

The elementary dipole–loop combination was used here to illustrate clearly the physical principles involved. Other antenna types and arrangements may be more suitable in practice. Also, only amplitude modulation was considered. Other types of modulation (phase or frequency) may also be discussed.

Since time-varying magnetic fields at radio frequencies can be detected down to very small values using ordinary conductors (about 10^{-10} T) and, in principle, to arbitrarily low values using superconductors, there do not appear to be any radical barriers in the way of realizing companion wave communication, at least for relatively short distances. It may be that, just as electric aperture antennae (such as the parabolic reflector) made satellite communication and radio-astronomy possible, so will ingeniously conceived 'magnetic aperture antennae' make companion wave communication possible. While one possible application of the suggestion of this communication is that it could expand the signal-carrying capacity of an existing radio link, other beneficial application directions may also be imagined. The question of propagation effects due to the companion wave in a material medium has been touched on elsewhere [3].

References

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